

ALFVÉN INSTABILITIES DURING ICRF MINORITY HEATING IN TFTR[#].

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Abstract

High power ICRF minority heating produces an energetic tail in the distribution function of the resonant ions. When the energy in this tail exceeds a certain threshold, various kinds of Alfvénic instabilities can be excited. In TFTR, it is found that modes whose frequencies decrease vs. time cause fast ion losses and in turn a reduced Rf heating efficiency, unlike the usual global TAE. The frequency decrease of the modes is found to correspond to a radial movement of the mode itself: modelling shows that this feature causes an avalanche of fast ion losses due to a diffusion process. The frequency-decreasing modes play a fundamental role in the stabilization of the sawtooth and in its subsequent crash.

1. INTRODUCTION

Instabilities in the Alfvén range of frequencies which are excited by energetic ions produced by ICRF heating^{1,2} can play a fundamental role in the energetic ion transport^{3,4} and in the dynamics of the giant sawtooth. Several modes, different in structure and with a variety of toroidal numbers can be destabilized^{5,6}.

Alfvén instabilities were observed in ICRF minority heating experiments in a variety of plasma conditions in TFTR. The great majority of the experiments were performed in deuterium plasmas with ICRF heating at the fundamental minority hydrogen resonance. Frequencies 43, 47 and 63,6 Mhz were used with corresponding magnetic fields to produce the cyclotron resonance on axis. The density ranged between 2 and $4.6 \times 10^{15} \text{ cm}^{-3}$. The plasma current varied between 1.2 and 1.8 MA, in such a manner that $q(a) \approx 3.2$ in the great majority of cases.

A set of Mirnov coils⁷ was used to detect the MHD activity. It consisted of a poloidal array to determine the poloidal mode number, m , whenever possible, and a toroidal array to determine the toroidal mode number n . The Mirnov data were compared with data from a reflectometer⁸ whenever available. Four probes placed at the edge of the plasma⁹ detected energetic ions ejected from the plasma through their interaction with the MHD activity.

2. EXPERIMENTAL RESULTS

Figure 1 shows the dependence of the steady-state total and thermal energies of the plasma on the injected rf power. Three regimes are distinguishable. At first, the increase is linear and equal for the total energy and the thermal component. In this regime, ion-ion collisions dominate and the minority ion distribution function does not present strong anisotropy¹⁰. Next, as the rf power and the minority ion energy increase, electron drag begins to dominate and an asymmetric part of the minority ion distribution function appears. During this phase, low levels of fast ion loss are detected. Finally, at higher power (~ 4 MW) fast ion losses increase drastically and the Mirnov coils detect a signal which increases linearly with power. In this regime, confinement is clearly degraded.

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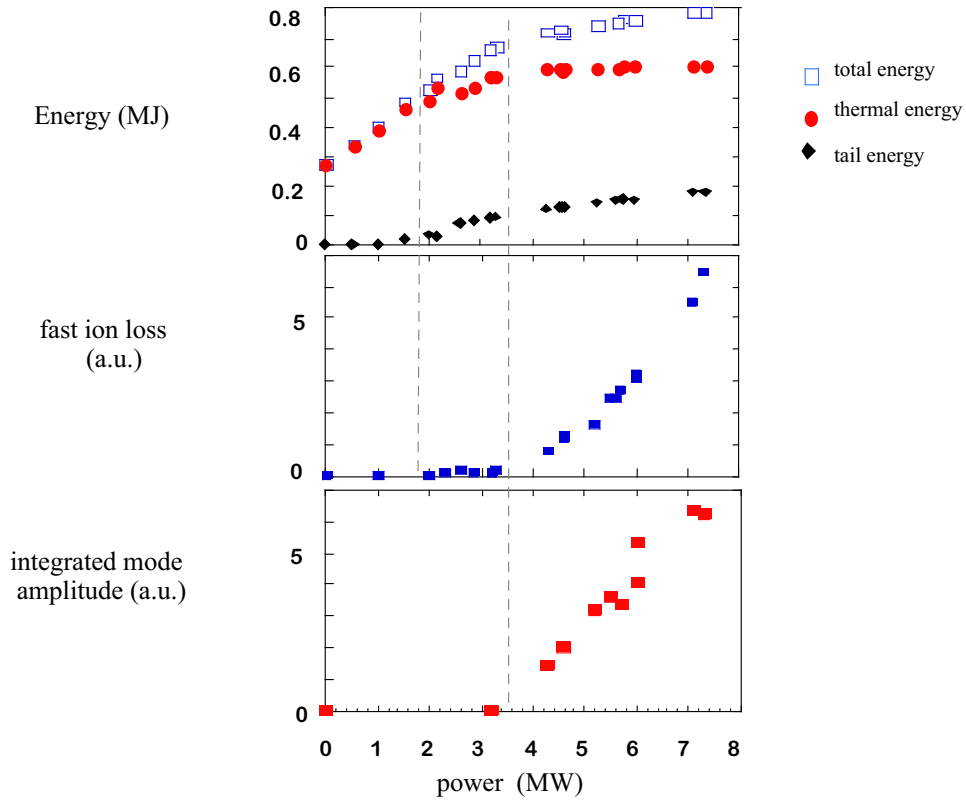


Fig. 1 Correlation between onset of MHD instabilities with fast ion losses and energy confinement degradation, versus rf power.

The Alfvén spectrum can display two groups of modes, as shown in Fig. 2: one “stationary” in the sense that the frequency follows very closely the $(n_e)^{-1/2}$ dependence characteristic of Toroidal Alfvén Eigenmodes (TAE)¹¹, and another group whose frequency decreases in time¹². Both groups are usually made of several modes with well defined toroidal numbers. The TAE are global modes that are readily detected by the Mirnov coils. Because of the lack of a simultaneous measurement of the q profile, it is difficult to identify the chirping modes, other than that they are measured to be core localized modes. They have a lower rf power threshold, in the sense that in power ramps or power scans they are destabilized first.

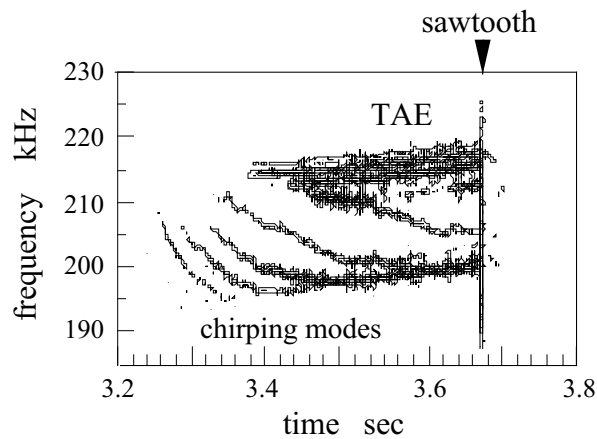


Fig. 2 Typical frequency spectrum from a Mirnov probe preceding a giant sawtooth crash.

Following their excitation, they appear to move radially outward. This is indicated by the fact that, before the Mirnov coils show their signature, they are detected as density fluctuations in the core by a microwave reflectometer¹¹. The chirping modes are destabilized sequentially with decreasing n number: this behavior is typical of what is expected for Energetic Particle Modes (EPM)^{4,6}. The chirping modes rather than the TAEs are observed to be responsible for most of the fast ion losses. Figure 3 shows the correlation between the onset of the chirping modes, the fast ion losses and the “clamping” of the total stored energy

At t=3.8 sec the fast ion losses increase sharply, the stored energy, which was recovering from the previous giant sawtooth, stops increasing and the spectrum of the TAEs is modified. It is at this time that the chirping modes are destabilized in the core, but are detected by the Mirnov loops with a delay of ~30 msec since this is the time it takes for them to propagate outward enough to be detected at the edge. During the time between the giant sawtooth and the appearance of the chirping modes, the TAEs are present, but do not prevent the stored energy from increasing.

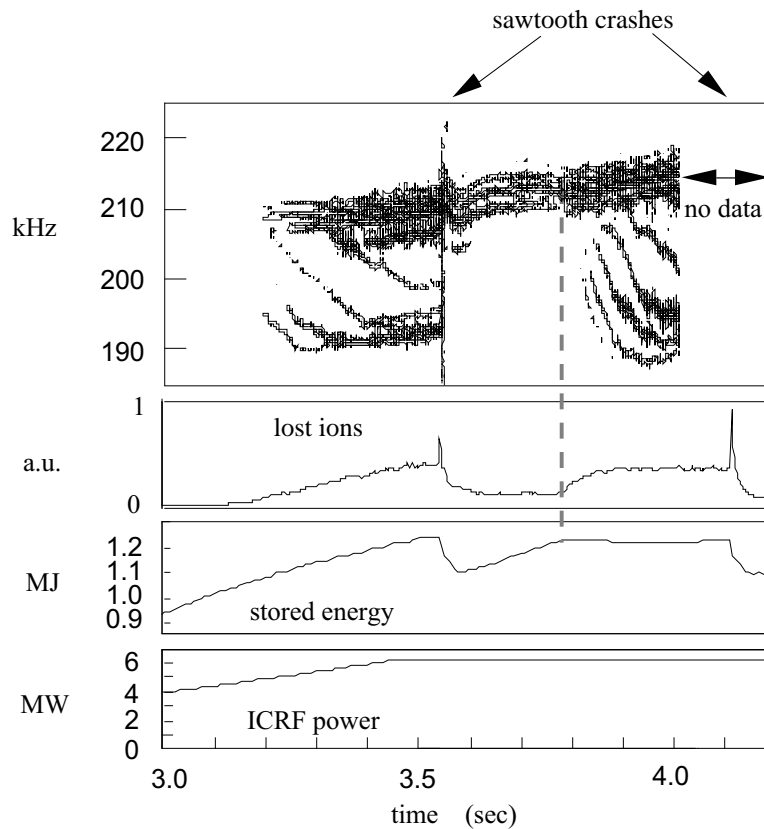


Fig.3 Correlation between Mirnov coil spectrum, lost ions, stored energy and rf power vs. time.

As seen at $t \approx 3.15$ sec, as the rf power reaches ≈ 4.5 MW the chirping modes appear: the TAE appear immediately after. The giant sawtooth generally terminates the chirping modes activity, while the TAE survive, with their frequency following the behavior of $(n_e)^{-1/2}$ at the location of the gap. Since the TAEs are localized outside the $q=1$ surface, the sawtooth causes an immediate increase of density and a decrease in mode frequency, followed by a slow recovery. In certain instances a shorter sawtooth appears and the subsequent displacement of fast ions causes a burst of TAEs, which lasts ≈ 30 msec without much consequence to the total energy. Similarly, it appears that the chirping modes initiate an avalanche of fast ions which in turn excite TAEs as they cross the gap.

That the chirping modes are causing a flow of fast ions from the core outward, is indirectly seen by the change of the spacing in frequency between the various modes of the TAEs. The spread in frequency of these modes is due to the Doppler shift caused by the toroidal rotation of

the plasma, with the frequency defined by $\omega_{\text{exp}} = \omega_{\text{real}} - n \omega_{\text{rot}}$ where ω_{exp} is the measured frequency, ω_{rot} the rotation frequency and ω_{real} the real frequency.

Taking the measured n-numbers we obtain at $t = 3.7\text{sec}$ $v_{\text{rot}} \approx 28$ km/sec, which is in very good agreement with the value of 30 km/sec typically observed in H minority experiments. At $t = 3.9$ sec we calculate $v_{\text{rot}} \approx 22$ km/sec, the decrease in rotation velocity being caused by $E_r \times B_q$, with E_r caused by the displacement of positive charge from the core outward.

The chirping modes appear to play a double role in the development of the giant sawtooth. First, by depleting the core of fast ions, they slow down the heating which could otherwise cause the peaking of the current profile which precedes the sawtooth crash: this is seen by noting that once the chirping modes are triggered, the crash is delayed until the sequence of decreasing frequency is followed by a stationary period. No matter how much power is applied, and most importantly, no matter what the amplitude of the chirping modes, the sawtooth crashes happen after typically $\sim 400\text{-}500$ msec, when the frequency stop decreasing. Second, because of the depletion of fast ions from the core, their stabilizing effect is not sufficient as the $q=1$ surface increases. This is inferred by the small upshift of the frequency of the TAEs, which are pushed to lower density by the $q=1$ broadening when there is a giant sawtooth crash. Previous theory¹³ suggests that sawtooth stabilization by fast particles is lost when the beta of the energetic particles inside the $q=1$ surface drops below a critical level.

3. DISCUSSION

The positive identification of the chirping modes is quite difficult and their actual amplitude and location in the plasma cannot be accurately inferred. Nonetheless, introducing radially stationary modes (TAEs) into the ORBIT¹⁴ code, with an amplitude of $\text{DB}/B \approx 5 \times 10^{-4}$, no significant fast ion losses are calculated. On the other hand, introducing modes which sweep a fraction of the radius with similar amplitude, an avalanche of lost banana-trapped ions is observed through a diffusive process. Assuming $\Delta B/B \approx 5 \times 10^{-4}$ and a radial sweep of half the minor radius, the losses are 30% of the total fast ion population for the experimental condition shown in figure 3.

The TFTR data described above pertains to discharges with $q(a)=3.2$. There are also a number of discharges with $q(a)$ up to 6.8: in these the phenomenology of the heating and the TAEs is the same (with the TAE's frequency scaling with q as expected) However, the chirping modes are not observed by the Mirnov coils. This is probably due to the fact that the chirping modes, whose frequency, after decreasing, settles on a certain value, might stop at a value of q too deep into the plasma to be detected at the edge in discharges at high $q(a)$.

These experiments in summary provide a direct mechanism for the loss of the fast ion beta and subsequent collapse of the giant sawtooth. Furthermore, they point to a potential threat to the confinement of alpha particles under reactor conditions if frequency sweeping modes are generated.

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